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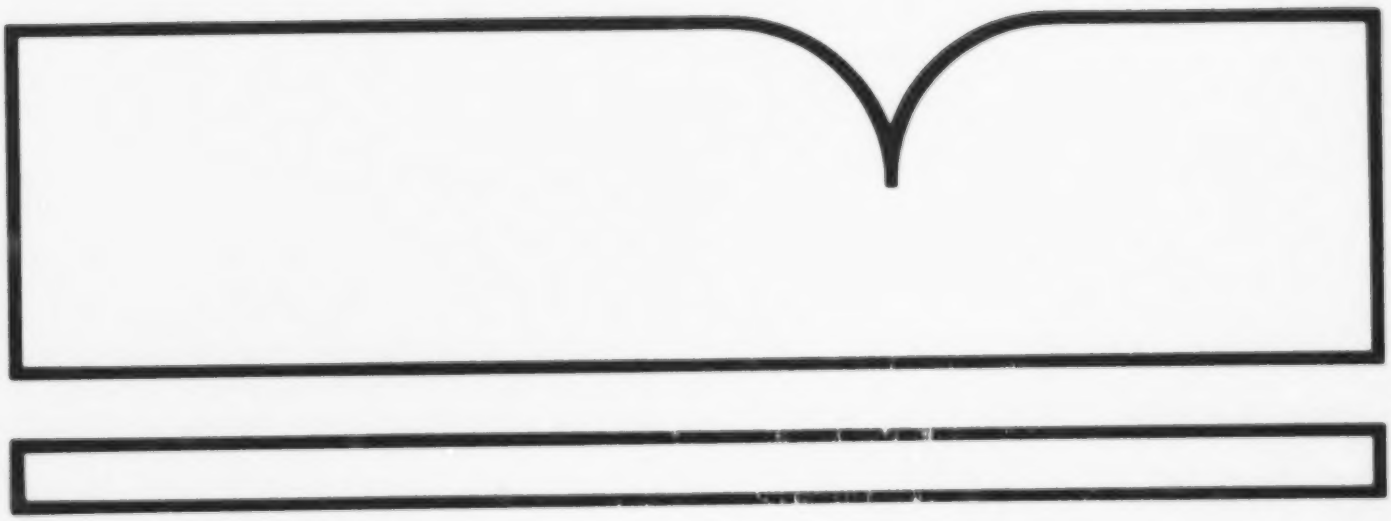

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Low NO_x Combustion Systems with SO_2 Control Using Limestone

by

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16. ABSTRACT The paper describes EPA work on low NOx combustion systems with SO2 control using limestone. Although SO2 control in low NOx systems for both stoker and pulverized-coal-fired furnaces is under investigation at EPA, most of the current work is with pulverized coal. EPA's Limestone Injection Multistage Burners (LIMB) program is an effort to develop an effective but inexpensive emission control technology for pulverized-coal boilers that will simultaneously remove SOx and NOx from boiler flue gases. The technology is based on the use of low NOx combustion techniques in combination with dry limestone injection into the furnace (combustion chamber) for simultaneous SOx control. The program goal is to develop the technology to obtain substantial reductions in SOx and NOx emissions for a capital investment cost of 30-40 $/kW--less than 20% of the capital cost of conventional flue gas desulfurization systems. For retrofits of the technology on existing pulverized-coal boilers, the goal is to achieve 50-70% SOx control and NOx emission levels of 130-170 ng/J thermal input. For new boilers, the goal is to achieve even higher SOx removals while achieving NOx emission levels of 86-130 ng/J. In addition, for new systems there exists the possibility of achieving synergism between the limestone injection process and various tailend cleanup devices for both particulate and SOx.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Limestone	Stationary Sources	08G
Coal	Limestone Injection Multistage Burners (LIMB)	21D
Flue Gases		21B
Nitrogen Oxides		07B
Sulfur Oxides		

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Low NO_x Combustion Systems with SO_2 Control Using Limestone

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INTRODUCTION

Although SO_2 control in low NO_x systems for both stoker and pulverized-coal-fired furnaces is under investigation at the Environmental Protection Agency (EPA), the majority of current work is with pulverized coal. The EPA Limestone Injection/Multistaged Burners (LIMB) program is an effort to develop an effective but inexpensive emission control technology for pulverized-coal boilers that will simultaneously remove sulfur oxides (SO_x) and nitrogen oxides (NO_x) from boiler flue gases. The technology is based on the use of low NO_x combustion techniques in combination with dry limestone injection into the furnace (combustion chamber) for simultaneous SO_x control.

The program goal is to develop the technology to obtain substantial reductions in SO_x and NO_x emissions for a capital investment cost of 30-40 $/kW - less than 20 percent of the capital cost of conventional flue gas desulfurization (FGD) systems. For retrofits of the technology on existing pulverized-coal boilers, the goal is to achieve 50-70 percent SO_x control and NO_x emission levels of 130-170 ng/J (0.3-0.4 lb/10^6 Btu) thermal input. For new boilers the goal is to achieve even higher SO_x removals while achieving NO_x emission levels of 86-130 ng/J (0.2-0.3 lb/10^6 Btu). In addition, for new systems there exists the possibility of achieving synergism between the limestone injection process and various tailend cleanup devices for both particulate and SO_x, thus producing a hybrid system which will be low cost and very effective (state-of-the-art) for combined SO_x, NO_x, and particulate. Such a process might combine, for instance, low NO_x burners, limestone injection, and an SO_x/particulate control system such as the spray-dryer/baghouse combination.

BACKGROUND

During the late 1960's and early 1970's the EPA and its predecessor organizations surveyed systems for air pollution control from coal-fired utility boilers. From this early work came developments such as limestone scrubbing for FGD, low NO_x combustion technology, fabric filtration with glass bags, and advanced electrostatic precipitator designs. The forerunner of limestone scrubbing for SO_x control was dry limestone injection. Typically, the limestone (either calcite or dolomite) was finely ground and fed into the boiler firebox above the flame zone, although some tests were made with limestone added to the coal. In a series of 19 projects

begun in the late 1960's, EPA studied the use of dry sorbents for SO_2 control from every aspect including: limestone characterization, limestone/SO_2 reaction kinetics, measurement of dispersion after injection, pilot scale tests at Peabody Coal Co. and at Babcock & Wilcox, full scale tests at TVA, and methods for utilization of flyash modified by calcium compounds.

In the tests at Babcock & Wilcox (1), the down-fired pilot plant was designed to burn up to 9 kg/hr of coal. At 29.3 kWt (kW thermal) and 15 percent excess air, sorbent injection ports were available at furnace temperatures ranging from 1480°C to 815°C. In 415 tests, a total of 129 different sorbents were studied while firing a variety of pulverized coals. Using up to double the calcium required, the degree of SO_2 control was between 21 and 34 percent, although some sorbents such as Michigan marl achieved better than 40 percent SO_2 control. There was a large scatter in capture for both calcites and dolomites, but the average of the two sorbents was essentially equal. Injection of extra sorbent did not improve control linearly but as the two thirds power. Injection of sorbent with the coal gave poor SO_2 control (less than 8 percent). Fine grinding of the coarse grained sorbent to surface areas greater than 1 m^2/g improved reactivity, and fine grained marls and hydrates with surface areas greater than 9 m^2/g were more reactive than other sorbents.

In the tests at Peabody Coal Company (2), the furnace was a chain grate stoker firing up to 200 kg/hr of coal. The fuel was 3.1 percent sulfur coal from western Kentucky. Only six sorbents were tested: two calcites, two dolomites, aragonite (a second crystalline form of calcium carbonate), and red mud (the dried tailings from the manufacture of alumina from bauxite). Furnace injection temperatures ranged from 980°C to 1315°C. SO_2 control ranged from 20 to 65 percent for the calcites. The aragonite was the best sorbent, followed by the calcites, then the dolomites. Red mud was not effective at all. Also, sorbent mixed with the coal was not effective. Calcium oxide utilization improved dramatically from 6.3 percent for plus 100 mesh (149 μm) particles to 59.5 percent for minus 200 mesh (74 μm) particles.

In the tests at TVA (3), the site was Unit 10 of the Shawnee Steam Plant firing coal at a nominal 150 MWe. Three sorbents were tested: aragonite and two calcites. One calcite was Michigan marl; the other was a fine-grained high-purity stone from Kentucky. Using twice the calcium required theoretically, the SO_2 control ranged from 17 to 20 percent, with the marl giving the best performance. The importance of time/temperature environment on SO_2 control was demonstrated by reducing the boiler to half load. At half load, the residence time at 926°C to 1204°C (the temperature range for the sulfation reaction) is increased, and the SO_2 control was as high as 36 percent. These results did not meet program objectives.

Years later, interest in limestone injection was revived as a result of extensive development work on advanced design low NO_x coal burners sponsored by the EPA and others. To achieve low NO_x emissions, the mixing of coal and air is delayed which results in reduced peak temperatures and altered chemical conditions in the reaction zone. As a result, in 1978 a short series of trials were carried out at Energy and Environmental Research Corporation (EERC) under EPA direction to study sorbent injection

through an advanced low NO_x burner (4). SO_x removals of up to 73 percent were achieved with limestone injection at a calcium-to-sulfur stoichiometry of two. These results were for an experimental 6×10^6 Btu/hr burner operating in a small experimental tunnel at conditions designed to minimize NO_x. No optimization of SO_x capture was attempted.

As shown in Figure 1, the advantage of this burner is the delayed mixing of fuel and air which lowers temperature and provides reducing gases which favor conversion of fuel nitrogen to N_2. The tests fired coal at a rate producing 3.5 MWt. Fuels used were a 0.7 percent sulfur Utah coal and a 3.8 percent sulfur Kentucky coal. Sorbents used included limestone and nahcolite which were mixed with coal for these tests. The SO_2 control achieved with limestone was 53 percent with low sulfur coal and 50 percent with high sulfur coal when the sorbent injection rate was at the stoichiometric requirement. At stoichiometric ratios of 2 and 3, the SO_2 control rose to 73 and 88 percent, respectively, with the low sulfur coal. In discussing these results, the following differences were noted using the distributed mixing burner (DMB) which might account for high levels of SO_2 control:

1) The low NO_x DMB provides an optimum time/temperature profile. Peak temperatures in the DMB are lower, giving less opportunity for the limestone to lose reactivity to deadburning. Longer residence times at lower temperatures provide more time for the sulfation reaction.

2) Peak flame temperatures occur under fuel-rich conditions where limestone can react with reduced sulfur species. Sulfidation reactions are faster than sulfation reactions, and the product calcium sulfide is more stable than calcium sulfate.

3) Effective sorbent distribution is provided by mixing sorbent with the coal.

In reference to the last point, previous studies (including those noted above) showed sorbent addition to the coal to be ineffective because of the high peak temperatures resulting in limestone deadburning in typical furnaces. However, since high peak temperatures and limestone deadburning may be avoided in the DMB, injection of sorbent with the coal is possible. This is a bonus of the combination of sorbent injection with the DMB because better mixing between sorbent and SO_2 is made possible.

Meanwhile, in Europe, several organizations made new efforts to utilize sorbents for SO_2 control from power plants. The Austrian Osterreichische Draukraftwerke AG tested sorbent addition at their Voitberg II plant rated at 65 MWe. This plant fired coal at 65 metric tons/hr, and the coal sulfur content ranged from 0.5 to 1.3 percent. Calcium hydroxide added to the coal gave 50 percent SO_2 control with flue gas recirculation and at a stoichiometric ratio of 4. The German Rheinish-Westfallische Electrizitatswerke (RWE) tested sorbent addition at their Fortuna II plant rated at 60 MWe. This plant fired brown coal with a sulfur content from 0.3 to 0.9 percent. Sorbents tested were calcite, dolomite, calcium hydroxide, and lime. Control of SO_2 ranged from 50 to 75 percent at stoichiometric ratios from 2 to 5. In Holland, the International Flame

Research Foundation tested calcium hydroxide injection into a pilot furnace with a distributed mixing burner and achieved 50 percent SO_2 control with a 0.8 percent sulfur coal and 70 percent SO_2 control with a 2.3 percent sulfur coal. The SO_2 control with limestone ranged from 30 to 40 percent with addition in the coal and 40 to 60 percent with separate injection. The German L. and C. Steinmuller Company currently is involved in testing sorbent injection into the Weiher power plant using retrofitted low NO_x burners.

While the limited U.S. pilot scale work was encouraging, additional work was clearly necessary to define the potential in U.S boilers. The limited capture relative to flue gas desulfurization systems did not provide strong incentive for stand-alone application to new boilers; however, the potential for combined systems appeared attractive. A strong incentive for further development of the approach emerged from an assessment of strategies available for retrofit control of acid rain precursors. SO_x and NO_x from pulverized coal-fired steam generators were major precursors to be considered. Based on a preliminary cost analysis it appeared that a LIMB technology to give 70% NO_x control and 50% SO_x control at a sorbent-to-sulfur ratio of 2 would be highly beneficial. On that basis in late 1979 EPA began laying the ground work for a development program for LIMB.

THE EPA PROGRAM

To define a LIMB program, it is necessary to examine the elements of the problem specific to the U.S. The key elements are:

1) The U.S. boiler population is made up of two main classes of boilers: those with rapid mixing burners (pre-NSPS wall fired boilers); and those with delayed mixing burners (tangential, arch fired, and post-NSPS wall fired). Within each class a number of additional design variables must be considered. To satisfy retrofit applications, the program must provide the basis for application to the full spectrum of boilers.

2) The U.S has a wide spectrum of coals ranging from low heating value lignites to high heating value bituminous. The properties of the coals vary widely, especially the sulfur level, distribution of sulfur type, and chemical composition of the ash content. The technology must be assessed for the full spectrum of coals, although emphasis should be placed on high sulfur eastern bituminous because of their heavy utilization in the northeast.

3) System optimization must be considered for new applications. High efficiency SO_x control is required to meet current NSPS (for new boilers), which will require either an optimization of the boiler/burner design or the use of a post-capture system for additional SO_x control. The program should provide a basis for new system design.

To satisfy these key elements, a program is structured to encompass five areas:

1) Basic understanding of the reaction mechanisms is essential to generalization of the technology. While a great deal of work has been done on the calcium/SO_2 reactions, the available data on the sulfide reaction mechanism are insufficient. In addition very little work has been done on sorbent sulfur reactions under actual coal combustion conditions. This information will provide input to the optimization of conventional systems.

2) Systematic small bench and pilot scale development of combustion technology is necessary for the wide range of boiler and fuel types. A wide range of variables must be examined, including: burner mixing, sorbent injection, thermal environment, sorbent type and stoichiometry, and coal properties. To quantify the effects, experiments must be run under well controlled conditions in as economical a manner as possible. The results must address not only SO_x and NO_x control, but also particulate related system effects such as slagging, fouling, and collection device efficiency.

3) Large pilot scale testing is required to extrapolate the performance of small scale experiments to practical scale. The testing should include optimization of full scale (nominal 100 x 10^6 Btu/hr) commercially available and advanced second generation low NO_x coal burners in an experimental system simulating practical boilers. These tests should include SO_x optimization as well as an evaluation of NO_x/SO_x tradeoff. Emphasis is being placed on burners suitable for retrofit applications. This portion of the program is being carried out with direct cooperation and participation of boiler and/or burner manufacturers. It will provide the final confirmation of the potential of LIMB technology for field application.

4) Process analysis is required to extrapolate the development data to practical boiler application and to identify potential operability/reliability problems for typical systems. It should also provide reliable cost estimates for both new and retrofit applications.

5) The Field application of the technology to representative boilers is the final step in the process. The current LIMB program does not encompass field demonstration of sorbent injection technology; however, it does provide design guidance for efforts by private industry.

RESULTS FROM THE EPA PROGRAM

Results to be discussed have come from the first, second, and fourth areas of the program as described above. To provide information in the first area, basic understanding, experiments were conducted in fixed bed and flow reactors described by Borgwardt et al. (5). Reaction rates of calcination and sulfidation of limestone were evaluated. Conclusions are:

1) The kinetics, as well as the thermodynamics, of sulfur capture by limestone in the reducing zone of LIMB are favorable. The

reaction rates observed are sufficiently fast to expect efficient sulfur capture in the reducing zone if no factors other than chemical kinetics limit the reaction.

2) Sulfur released as H_2S in the reducing zone of LIMB can be captured by limestone after calcination, but not by direct reaction with limestone. Consequently, the variables which affect calcination, and consequent porosity, and surface area can be expected to play a crucial role.

3) The laboratory techniques utilizing kinetic data from differential reactors appear to yield reliable estimates of the results obtainable in injected systems. The phenomena that are probably responsible for sulfur capture in LIMB (whether in the reducing or oxidizing zone) can be reproduced and studied under controlled laboratory conditions.

4) Extremely high sorbent surface areas can be achieved by the controlled calcination of limestone to calcium oxide. The sulfur capture reaction rates are affected proportionally by the available surface area.

Results from the second area, small bench and pilot scale testing, have been extensive. Equipment and facilities used for these experiments have been discussed by Drehmel et al. (6). Data from tests in a wall fired furnace show that SO_2 capture varies from 10 to 70 percent (at 2 times stoichiometric ratio) with extreme sensitivity to furnace and injection parameters.

Questions which this work is attempting to answer are:

1) What time/temperature profile does the limestone particle experience?

2) Is the limestone particle fully calcined and, if so, is there any loss of reactivity to deadburning?

3) What time/temperature profile does the coal particle experience?

4) When is the sulfur liberated from the coal and in what form?

5) Is there a critical temperature at which there must be sufficient residence time to promote the capture of sulfur species by limestone?

6) Is there loss of captured sulfur because of particle recirculation or because of a secondary flame associated with the staged combustion?

To answer these questions, test matrices were run to observe the effects of both H_2S-doped propane firings (in addition to coal firing tests) and delayed addition of combustion air (in addition to the use of the low NO_x distributed-mixing burner (DMB)). Delayed addition of air provides a long residence time (approximately 1 sec) of completely reducing conditions and

is referred to as external staging.

A limited comparison of DMB versus external staging for coal firing is shown in Figure 2. The abscissa is the usual calcium-to-sulfur mole ratio which has been modified by the square root of SO_2 concentration to account for varying SO_2 levels generated by different burns of coal. The SO_2 capture observed for the uncooled, externally staged condition is similar to the SO_2 capture for the DMB with cooling. The DMB without cooling provided a much poorer environment for SO_2 capture. A possible explanation is that the cooler conditions associated with external staging or with actual cooling provide a less likely environment for limestone deadburning which is suspected in the uncooled DMB case.

A comparison of DMB versus external staging for propane is shown in Figure 3. In this case, the performance in the uncooled DMB is much better than with external staging. This is contradictory to the previous explanation because the higher temperature of the uncooled DMB case should have caused the same deadburning suspected for the coal-firing case. Figure 3 also shows that the presence of long reducing conditions associated with external staging is not necessary for good sulfur capture.

The question of the effect of temperature can be further clarified by Figure 4. In this figure, coal and propane firing data are compared side by side. The line graphs give the temperature profiles, and the bar graphs give the sulfur capture. For these two runs the temperature profiles for both coal and propane firing are very similar. However, the performance of the limestone in capturing sulfur is at least a factor of 3 better in propane-firing than in coal-firing. Again, this rules out the effect of deadburning of the limestone because the performance is radically different with similar temperature profiles. It also argues against the importance of residence time in a critical temperature range for sulfur capture as the prime variable for this data set. Moreover, it demonstrates poor performance where loss of captured sulfur from a secondary flame cannot be the issue. In narrowing down the list of critical parameters, it would appear that unfavorable sulfur chemistry is the explanation for the poor SO_2 capture with coal firings. This could be a problem either in liberating sulfur from the coal or in not having enough time for the liberated sulfur to transform to the most reactive form and combine with limestone. However, Figure 3 illustrates that residence time of reactive reduced forms of sulfur (H_2S and COS) is not the critical parameter. Hence, the explanation at this point might be that liberation of sulfur from the coal was the critical parameter.

The final comparison is shown in Figure 5. Again data for coal and propane firings both without cooling and under the same conditions are displayed. In addition, SO_2 capture for coal firing with cooling is shown to be worse than for propane-firing but better than that for uncooled coal-firing. Unfortunately, this is contradictory to the explanation from Figure 4 because the cooled coal-firing could have been expected to have a slower sulfur liberation rate from the coal than that for the uncooled coal-firing. An alternative explanation that could explain all of the data is that some chemical species liberated from the coal inhibit the capture of sulfur species by limestone. At this time there is no direct evidence from these studies for such an explanation except that there are data to show reduced SO_2 capture by limestone when fly ash is injected into a gas flame.

Preliminary results from the fourth area, process analysis, have yielded estimates of cost for different control situations. The preliminary cost analysis was based on a 300 MWe pulverized-coal-fired boiler, operating at 40 percent capacity, and with an assumed remaining life of 15 years. These assumptions are typical of Eastern U.S. coal-fired utility boilers. Table 1 compares LIMB with the three most important SO_2 removal technologies: lime/limestone FGD, lime spray drying, and physical coal cleaning. The LIMB cost figures are based on a study by Combustion Engineering sponsored by EPRI (7). Also included are low NO_x burners, which (without the LIMB modification) can only control NO_x.

Note that, on the basis of levelized costs, the LIMB technology will be able to achieve 50-60 percent SO_2 reduction at costs: approximately 25 percent that of lime/limestone flue gas desulfurization, and about 30 percent that of lime spray drying. Although the levelized cost of LIMB may be somewhat higher than the cost of physical coal cleaning, the latter technology generally provides only a 20-30% reduction in potential SO_2 emissions since it is unable to remove the organic sulfur embodied in coal. Additionally, these coal cleaning costs are premised on a large centralized coal cleaning plant that washes coal for many plants.

Table 2 summarizes costs for a hypothetical "maximum control strategy" for Eastern U.S. coal-fired utility boilers. This scenario conservatively assumes that all high sulfur coal (greater than 1.5 percent) utility boilers east of the Mississippi would be retrofitted with one of the technologies listed. As can be seen, a LIMB control approach would save many billions of dollars over conventional lime/limestone FGD and lime spray drying; and for approximately the same cost LIMB would achieve 2.5 times the hydrogen ion reduction associated with a coal cleaning control strategy. The last column illustrates that LIMB would cost approximately one-third what lime/limestone FGD or lime spray drying would cost to achieve a given number of tons of hydrogen ion control. This column also illustrates the cost effectiveness of low NO_x burners: they represent the least expensive way of reducing potential hydrogen ion emissions. However, since only NO_x can be controlled, the quantity of acid rain precursors precluded is necessarily limited.

CONCLUSIONS

Data from fundamental research show that the sulfur capture mechanisms are fast enough to provide the control as stated in the program goals. Data from pilot scale research have verified SO_2 control efficiencies in the 50 to 70 percent range with indications of how to guarantee this performance in unknown applications. Results from process analysis indicate costs that are competitive with other control strategies and that will save billions of dollars. To counterbalance these optimistic findings is the fact that a number of engineering problems are not yet resolved; the most significant are:

- The fundamental chemical kinetics of sorbent activation and chemical reaction with the combustion gas sulfur species must be better understood before engineering can be scaled up with a reasonable degree of confidence.

- The effect of the sorbent additive on boiler plugging, slagging, and fouling must be determined. It is important to avoid introducing any boiler operating problems that could adversely affect reliability.

- For retrofits, the potential for adverse effects of the sorbent on the performance of the existing particulate collection equipment must be determined. It is important to determine if precipitator upgrading will be required or if relatively inexpensive flue gas treatment systems will allow for adequate particulate control in light of the increased quantities and poor electrical properties associated with the flyash/calcium compound particulate.

Under the EPA program these problems are being studied to make possible early application of LIMB technology.

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Table 1 Control Technologies for a Typical 300 MWe Coal-Fired Utility Boiler

	Lime/Limestone FGD	Lime Spray Drying	Physical Coal Cleaning[b]	Limestone Injection in Multistage Burners	Burners (NO_x Control Only)
Technical Status	Commercial	Early Commercial	Commercial	Developmental	Early Commercial
SO_2/NO_x Removal Efficiency	90% SO_2 Reduction	75% SO_2 Reduction	20-30% SO_2 Reduction	50-60% SO_2 Reduction 50-60% NO_x Reduction	60-70% NO_x Reduction
Capital Investment ($/kW)[a]	260	190	46	27-37	2.0-7.1
Annual Operating Expense (mills/kWh)[a]	6.4	5.7	1.7	3.1	0.05
Levelized Annual Revenue Requirement (mills/kWh)[a]	23	18	4.9	5.6-6.1	0.2-0.4

a) Costs expressed in December 1982 dollars, assuming a remaining boiler life of 15 years and a 40% operating factor.

b) Coal cleaning costs presented are based on a central plant sized for 2000 MWe operating at 9500 Btu/kWh and 5500 hrs/year. Cost benefits that may accrue from reduced transportation expense and reduced boiler O&M for a cleaned coal were not included.

Table 2 Comparative Costs of Hypothetical Maximum[a] Control Strategies for Eastern U.S. Coal-Fired Utility Boilers

Technology	Net Capital Investment[a] (10^9)	Net Levelized Annual Revenue Requirement[b] (10^9)	Ten Year Cost[c] (10^9)	SO_2 Reduction[d] (10^6 tons per year)	NO_x Reduction[e] (10^6 tons per year)	H^+ ion Reduction[f] (10^3 tons per year)	Cost/Benefit Ratio (10^3/ton H^+ Reduction - 10 Year Average)
Lime/ Limestone FGD	26	8.1	65	8.3	-	260	31
Lime Spray Drying	19	6.3	50	6.9	-	220	29
Physical Coal Cleaning	4.6	1.7	14	2.3	-	72	24
Limestone Injection Multistage Burner	2.7-3.7	2.0	16	5.1	2.5	180	11.3
Low NO_x Burners (NO_x Only)[g]	0.37-1.3	0.13-0.26	1.0-2.0	-	2.5	54	2.4-4.8

a) Assumes retrofit of SO_2 control technologies to all Eastern U.S. utility boilers whose primary fuel is coal with greater than 1.5 percent sulfur. For all states east of the Mississippi River this is about 100,000 MW when 19,000 MW already with FGD is excluded. (Data provided by Pechan and Associates and PEDCo Environmental.) For low-NO_x burners, retrofit to 187,000 MW of total existing coal-fired capacity in Eastern U.S. was assumed. All costs in December 1982 dollars.

b) Assumes 40% average plant capacity factor.

c) Net 10 year levelized revenue requirement based on 5 year implementation period with 10 percent implementation for 1st year, 20 percent for 2nd, 40 percent for 3rd, 20 percent for 4th, and 10 percent for 5th.

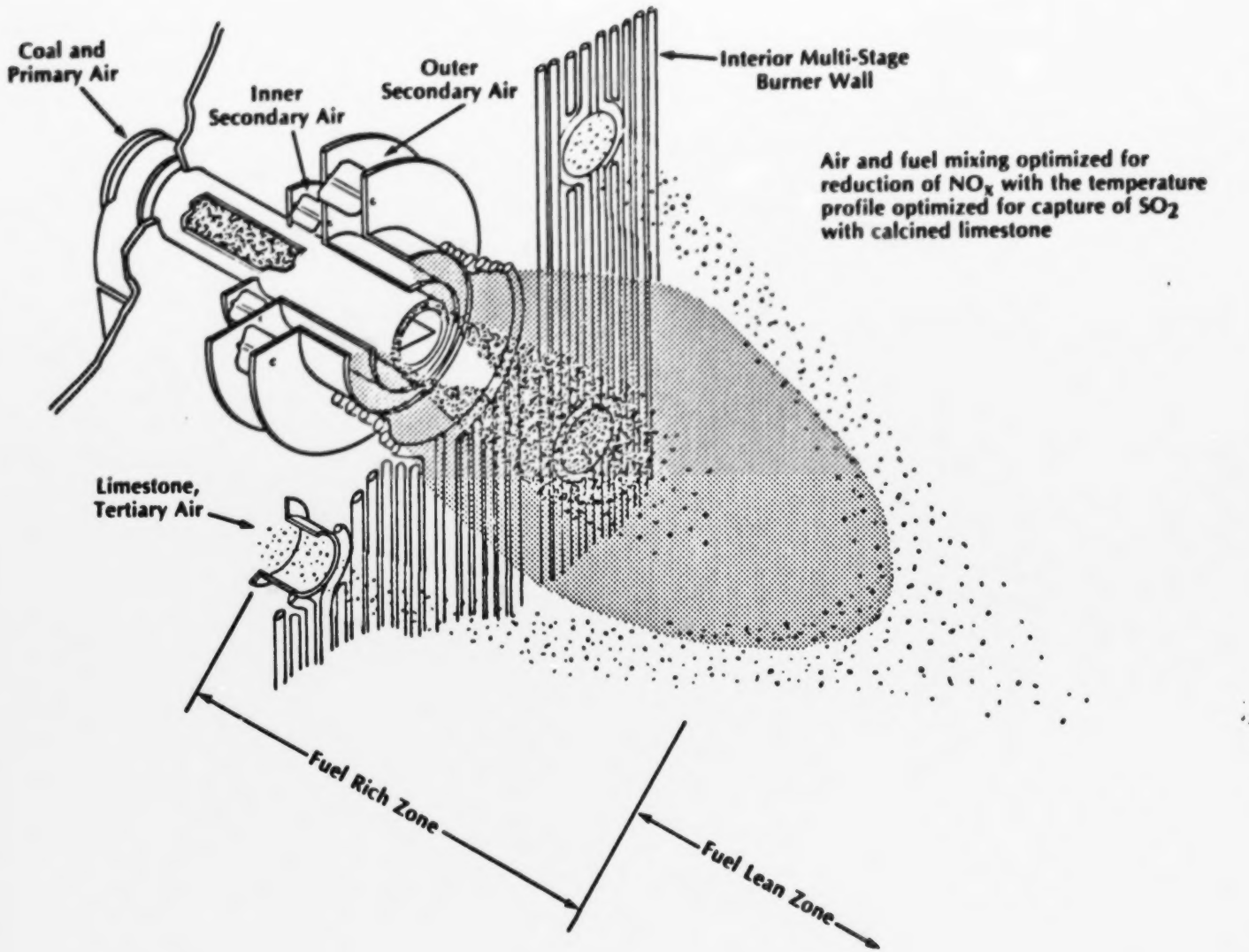
d) Total current Eastern U.S. SO_2 emissions from coal-fired utility boilers burning greater than 1.5 percent sulfur coal and not employing FGD estimated at 9.2 million tons per year.

e) Total current Eastern U.S. NO_x emissions from coal-fired utility boilers estimated at 3.8 million tons per year, with an estimated 2.0 million tons per year from the 100,000 MW firing coal with a sulfur content greater than 1.5 percent.

f) Equivalent tons H^+ ion defined as tons SO_2 x (2/64.06) + tons NO_x (1/46.01).

g) The range is given because the cost for low-NO_x burners for tangentially fired boilers is substantially lower than the cost for wall-fired boilers.

Figure 1
Limestone Injection Multi-Stage Burner for Simultaneous NO_x and SO_x Control


Coal and Primary Air
Inner Secondary Air
Outer Secondary Air
Interior Multi-Stage Burner Wall
Air and fuel mixing optimized for reduction of NO_x with the temperature profile optimized for capture of SO_2 with calcined limestone
Limestone, Tertiary Air
Fuel Rich Zone
Fuel Lean Zone

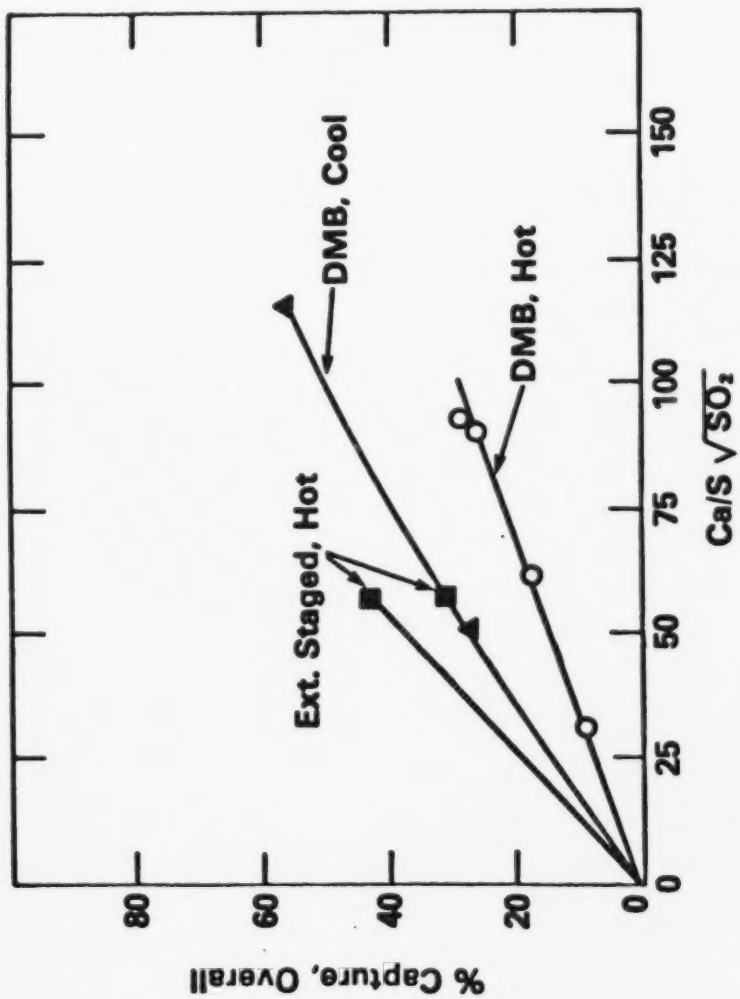


Figure 2
Comparison of Firing Systems, Coal Fired

Figure 3
Comparison of Firing Systems, Propane + H_2S, Uncooled

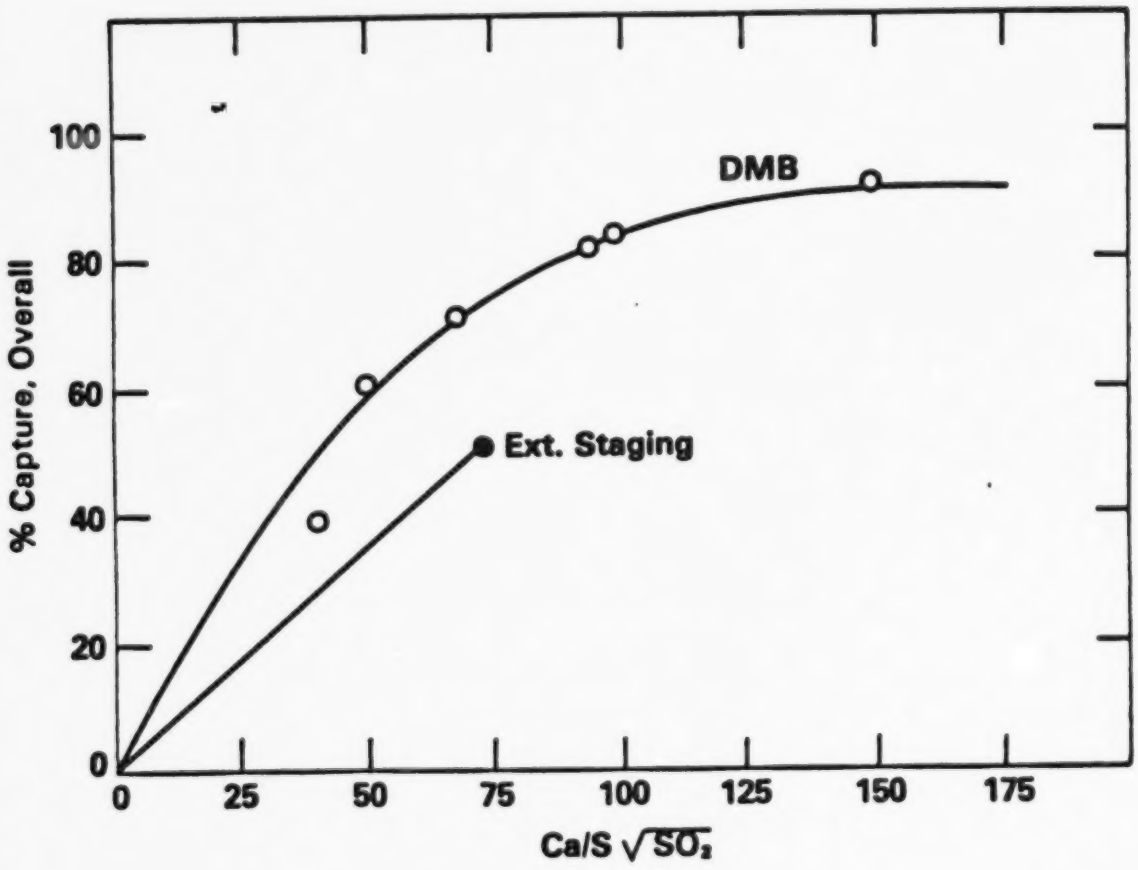
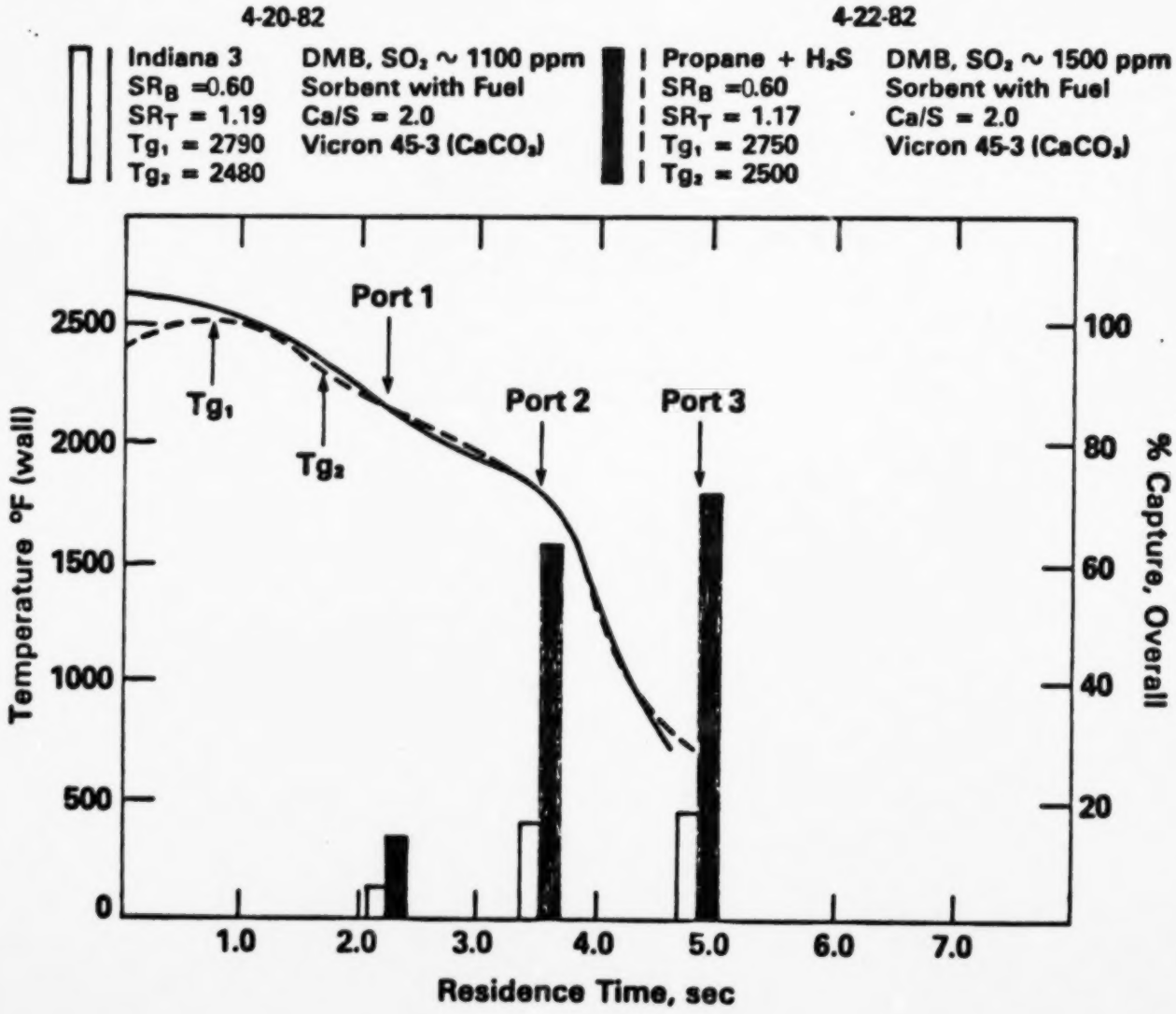


Figure 4
Comparison of Coal and Propane Capture and Thermal History



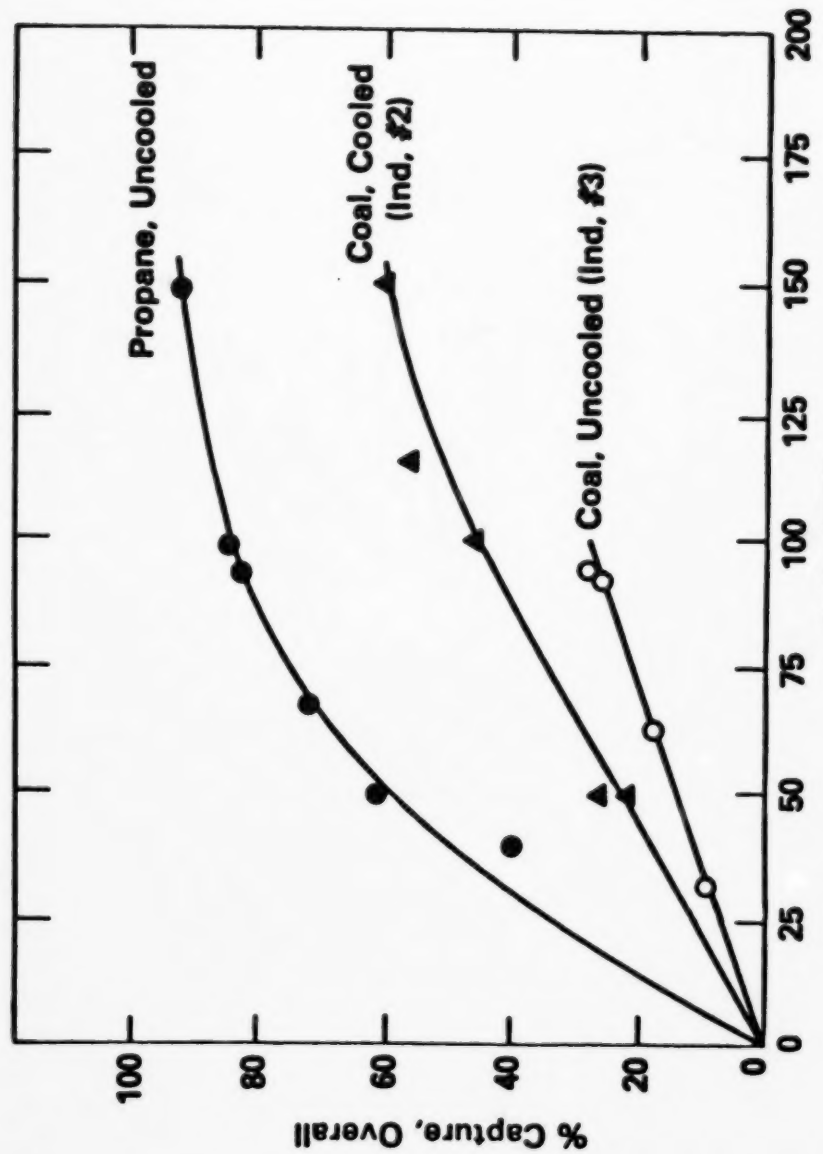


Figure 5
Comparison of Overall Capture, DMB, Various Conditions